

The Effect of Force on Fingerprint Image Quality and Fingerprint Distortion

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Article Info

Article history:

Received Feb 23, 2013
Revised Apr 15th, 2013
Accepted May 17, 2013

Keyword:

Fingerprint quality
Fingerprint distortion
Correlation coefficient
Non-parametric method
U test

ABSTRACT

The purpose of this paper is to investigate fingerprint quality and quality problems due to nonlinear elastic distortion. The effect of force on fingerprint quality was studied using computation and analysis of the correlation coefficient r between the fingerprint quality score and force. The correlation analysis results show that fingerprint quality is significantly attributed to force. Based on the *U* test, a comparative study between male and female students about the fingerprint quality was conducted. At the 0.05 level of significance, there is a significant difference between male and female students in the fingerprint quality of the flat left thumb at a greater force level and in the fingerprint quality of the slap left fingers at all force levels.

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1. INTRODUCTION

Fingerprint recognition is one of the foremost and most often used methods in biometrics. It has been used in criminal identification, computer access or login security, in a wide area of healthcare systems, and in Homeland Security for e-passports and border access control. Since September 11, 2001, fingerprint recognition has become an advanced tool to fight against terrorism.

A flat fingerprint (also known as plain fingerprint or plain impression) can be obtained if a finger is pressed down on a platen (scanner) but not rolled. Rolled fingerprint images are obtained by rolling a finger from one side to the other ("nail-to-nail") in order to capture all of the ridge details of a finger [1]. A slap fingerprint refers to fingerprints simultaneously captured in a single image by pressing four fingers of one hand onto a platen or a fingerprint card. Slaps are also known as four finger simultaneous plain impressions. The four fingers are little finger, ring finger, middle finger, and index finger [2]. Flat fingerprints cover a smaller area than rolled fingerprints; have fewer minutiae; but are less distorted; and therefore have clearer ridges [3]. Flat fingerprints can be acquired quickly with little operator training. Rolled fingerprints provide a great deal of information, but properly rolling fingerprints is a slow process and operators must be trained to collect good quality rolled fingerprints [4].

Figure 1 shows a flat fingerprint and a rolled fingerprint and their image quality scores of the author of this paper. The fingerprints and the image quality scores were captured using the ID 500 10-Print Live Scan System [2].

A single flat finger is frequently used for verification systems such as access control systems, small to medium-sized identification systems, and occasionally for large-scale identification systems, such as the Immigration and Naturalization Service (INS) Automated Biometric Identification System [4]. In law-enforcement applications, fingerprints are generally taken by rolling each finger "nail-to-nail", and individual

records contain prints from all 10 of a person's fingers. Biometric identification (or verification) situations on the other hand, generally only contain records of one or two of a person's fingers. The records are generally taken by simply placing a finger on the surface instead of rolling it, yielding perhaps only half as much information [5]. A slap fingerprint can improve performance accuracy and efficiency over a single flat finger because four fingerprints are collected in a single image [2]. Originally, slap fingerprints were collected so that the sequence of rolled fingerprints could be double-checked; however, slap fingerprints have received a great deal of interest as a means of easily collecting multiple flat fingerprints with a high quality at once [4].

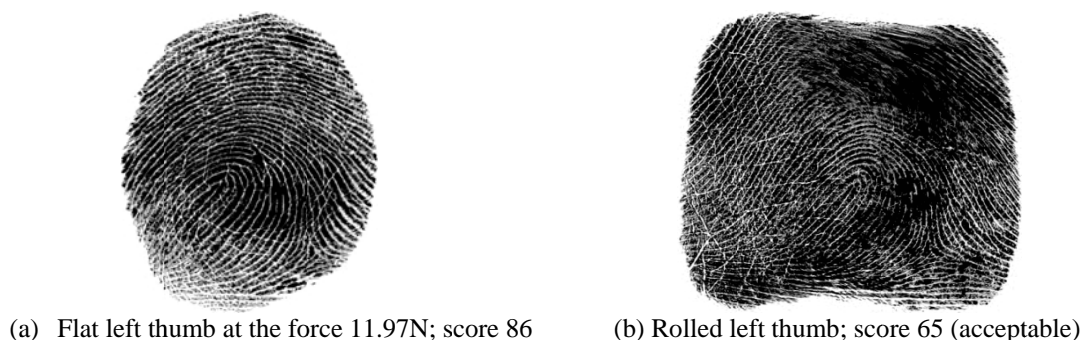


Figure 1. A flat fingerprint and a rolled fingerprint with image quality scores

A fingerprint with a digital image can be captured from the live scan. An ideally scanned fingerprint image has clear and distinct ridges and valleys. However, fingerprint images sometimes have quality problems due to various reasons. Poor fingerprint images often result from dry skin and damaged sensor plates; cuts or abrasions on fingers; diseased fingers; dirt, oil, sweat, humidity or moisture on fingers or the scanner; non-uniform and inconsistent contact and partial imaging of the finger tip [5], [6], [7], [8]. The image for wet or sweaty fingers reflects black areas without line definition. A dry-finger image contains white areas and breaks in line definition. If the fingerprint is too narrow, without enough side-to-side coverage, deltas do not show up. Greasy silicon pad or platen can also cause poor fingerprint quality [2].

Poor-quality fingerprints are predominately due to non-uniform and inconsistent contact [9]. The acquisition of a fingerprint is a three-dimensional (3D) to two-dimensional (2D) mapping process where the 3D elastic surface of a finger is pressed onto the 2D flat sensor surface. During the acquisition process, nonlinear distortion is introduced due to the 3D–2D mapping, the elasticity of the skin, and the applied pressure especially if the force is not orthogonally applied to the sensor [10], [11]. Pressure differences can cause spatial scaling of the location of all features [8]. The nonlinear distortion in the fingerprint ridge structure mainly due to skin elastic deformation changes the position and orientation of minutiae and causes features such as minutiae points and ridge curves to be distorted [12]. Ridge endings and bifurcations may disappear when a finger is pressed too hard or too lightly [13].

High matching performance can be achieved if fingerprint quality is good. The distortion and other fingerprint quality problems can cause failure in enrollment and increase false accept rates (FAR) and false reject rates (FRR) [14] in fingerprint recognition. Therefore, fingerprint image quality is very important for a fingerprint recognition system. Fingerprint image quality and fingerprint distortion are related to pressure or force during the fingerprint capture process. The purpose of the research in this paper is to perform the following comparative study: 1) fingerprint images and scores at different force levels; 2) correlation analysis of fingerprint quality and force, and explanation of fingerprint distortion; 3) a non-parametric analysis based on the U test for male and female student fingerprint quality.

2. FINGERPRINT IMAGE QUALITY AT DIFFERENT FORCE

2.1. The Fingerprint Images and Quality Scores of the Flat Left Thumb

The ID 500 10-Print Live Scan System (developed by Cross Match Technologies, Inc.) was used to study the effect of force levels on fingerprint image quality and fingerprint distortion in this paper. The Live Scan Management Software (LSMS) 6.5 was installed in the system. The system is a fully FBI-compliant scan system with optical sensors. It has a single fixed capture platen and contains no moving parts. The fingerprint image illumination technology is fully computer controlled for optimal image uniformity. The

fingerprint image quality score is from 0 to 100. The lowest value is fixed at 0 and the highest value is fixed at 100 [2].

The fingerprint images of the flat left thumb at three force levels were captured using the ID 500 10-Print Live Scan System. At first, the left thumb was placed on the platen; the finger should be flat, straight, natural, and relaxed (without the introduction of a force or stress). A thick layer of padding material (weight is negligible) was put on the finger. An item with the weight of 0.45N, 11.97N, or 27.71N was put on the thick padding material. The three weights represent three force levels. The thick padding material was put between the item and the finger to make the force approximately evenly distributed on the finger. The flat fingerprint images and image quality scores for the left thumb are shown in Figure 2. There are white areas and line breaks in Figure 2 because too little force (or pressure) was applied to the finger. Figure 2 (b) indicates good quality because the right force was applied. Figure 2 (c) shows dark areas in the image because too much force (or pressure) was applied to the finger. Too much force introduced large nonlinear elastic distortion in the fingerprint ridge structure, which led to a poor and unacceptable fingerprint image.



Figure 2. The flat fingerprint images and quality scores of the left thumb at three force levels

2.2. The Fingerprint Images and Quality Scores of the Slap Left Fingers

During the image capture process of the slap left fingers, a thick layer of padding material was put on the four fingers to make the exerted force approximately evenly distributed on the fingers. An item with a weight of 0.98N, 17.22N, or 32.25N was put on the thick padding material. Slap left fingerprint (left four-finger simultaneous fingerprint) images and image quality scores are shown in Figure 3. The four left fingers are: left little finger, left ring finger, left middle finger, and left index finger. Figure 3 (a) shows unacceptable fingerprint quality because too little force (or pressure) was applied on the fingers. Figure 3 (b) indicates normal fingerprint quality as the right force was applied. Figure 3 (c) shows dark areas in the image and unacceptable fingerprint quality because there was too much force. The high force introduced large nonlinear elastic distortion in the fingerprint ridge structure and resulted in the unacceptable slap left fingerprint.





(c) 32.25N force; quality score 0 (unacceptable)

Figure 3. Slap left fingerprint images and quality scores at three force levels

3. RESULTS AND ANALYSIS

3.1. Data and Descriptive Statistics for Fingerprint Quality Scores

This fingerprint experiment was conducted in September 2012. 24 participants were university students (14 male students and 10 female students) and were 18-25 years old. Each student’s fingerprint quality scores for the flat left thumb at seven force levels were obtained. The seven force levels are: 0.98N, 3.47N, 5.87N, 9.39N, 11.97N, 17.22N, and 21.17N. Each student’s fingerprint quality scores for slap left fingers at the next seven force levels were obtained. The next seven force levels are: 3.60N, 6.18N, 9.39N, 11.97N, 17.22N, 21.17N, and 24.24N. Figure 4 shows a student’s fingerprint quality scores of the flat left thumb at seven force levels; Figure 5 shows the same student’s fingerprint quality scores of the slap left fingers at the next seven force levels.

In Figure 4 and Figure 5, the fingerprint quality score increases as force increases; then decreases as force increases. Force has a great impact on fingerprint quality. There is no incremental benefit in terms of fingerprint image quality when force is greater than a value. The value is 11.97 N in Figure 4 and 17.22N in Figure 5. Among the 24 students, eight students' flat fingerprint quality scores got to maximal values when the force is 9.39N; ten students' slap fingerprint quality scores got to maximal values when the force is 11.97N.

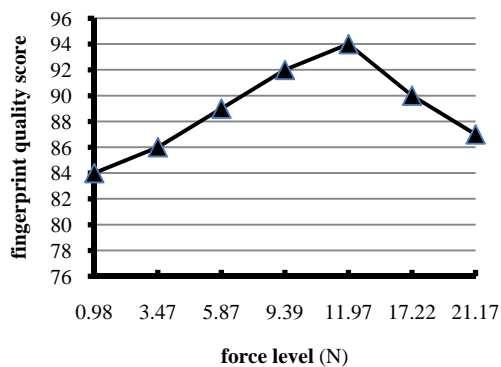


Figure 4. A student’s fingerprint quality scores for the flat left thumb at seven force levels

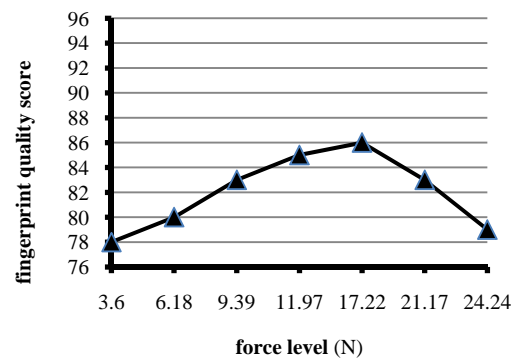


Figure 5. A student’s fingerprint quality scores for slap left fingers at seven force levels

Table 1 shows the mean μ and standard deviation σ of the fingerprint quality scores for the 24 students’ flat left thumbs at each force level. The mean increases as force increases; the mean then decreases as force increases. There is no incremental benefit in terms of the mean of quality scores when using more than 11.97N.

Table 1. The mean μ and standard deviation σ of the fingerprint quality scores of the flat left thumb at seven force levels

| Force level (N) | 0.98 | 3.47 | 5.87 | 9.39 | 11.97 | 17.22 | 21.17 |
|-----------------|------|------|------|------|-------|-------|-------|
| μ | 84.8 | 88.4 | 92.6 | 94.1 | 95.0 | 92.6 | 89.7 |
| σ | 8.48 | 7.11 | 4.01 | 3.83 | 4.85 | 6.51 | 6.33 |

Table 2 shows the mean μ and standard deviation σ of the fingerprint quality scores for the 24 students' slap left fingers at each force level. The mean increases as force increases; the mean then decreases as force increases. There is no incremental benefit in terms of the mean of quality scores when using more than 17.22N. The descriptive statistics for the quality scores in Table 1 and Table 2 exhibit the effect of force on fingerprint quality.

Table 2. The mean μ and standard deviation σ of the fingerprint quality scores of slap left fingers at seven force levels

| Force level (N) | 3.60 | 6.18 | 9.39 | 11.97 | 17.22 | 21.17 | 24.24 |
|-----------------|-------|-------|------|-------|-------|-------|-------|
| μ | 79.4 | 82.4 | 84.7 | 86.0 | 86.3 | 83.0 | 79.7 |
| σ | 10.37 | 10.03 | 9.97 | 9.36 | 9.52 | 9.65 | 10.11 |

3.2. The Coefficient of Correlation and Correlation Analysis for the Fingerprint

Of the variation in fingerprint quality scores, how much can be attributed to the relationship between the fingerprint quality score and force? How much can be attributed to chance or other factors such as fingerprint capture operation, wet or sweaty fingers, or dry fingers, etc.? To this end, the coefficient of correlation r between the fingerprint quality score and force was computed using the following method [15]:

$$r = \frac{S_{xy}}{\sqrt{S_{xx} \cdot S_{yy}}} \quad (1)$$

Where:

$$S_{xx} = \sum x^2 - \frac{(\sum x)^2}{n} \quad (2)$$

$$S_{yy} = \sum y^2 - \frac{(\sum y)^2}{n} \quad (3)$$

$$S_{xy} = \sum xy - \frac{(\sum x)(\sum y)}{n} \quad (4)$$

In these equations, y is the fingerprint quality score; x is the force; and n is the number of pairs (fingerprint quality score and corresponding force).

The coefficient of correlation r measures only the strength of linear or approximately linear relationships. In Figure 4 and Figure 5, data was plotted to see the relationships between the fingerprint quality score and force.

In Figure 4, there is an approximate linear relationship with a positive correlation ($r > 0$) between the fingerprint quality and force when force is between 0.98N and 11.97N; there is an approximate linear relationship with a negative correlation ($r < 0$) when force is between 11.97N and 21.17N. Considering that eight students' fingerprint quality score receive maximal values when the force is 9.39N among the 24 students, r values were calculated from 0.98N to 9.39N and from 11.97N to 21.17N, respectively. The force from 9.39N to 11.97N can be regarded as a transition interval.

In Figure 5, there is an approximate linear relationship with a positive correlation ($r > 0$) between fingerprint quality and force when force is between 3.60N and 17.22N; there is an approximate linear relationship with a negative correlation ($r < 0$) when force is between 17.22N and 24.24N. Considering that ten students' fingerprint quality score got to maximal values when the force is 11.97N among the 24 students, r values were calculated from 3.60N to 11.97N and from 17.22N to 24.24N, respectively. The force from 11.97N to 17.22N can be regarded as a transition interval.

When $r > 0$, the fingerprint quality score increases with the increase of force; when $r < 0$, the fingerprint quality score decreases with the increase of force. For the 24 students' flat left thumb fingerprint quality, all r values for the force between 0.98N and 11.97N are greater than 0.899; and all r values for the force between 11.97N and 21.17N are less than -0.891. The mean μ and the standard deviation σ of r for the flat left thumbs of 24 students are shown in Table 3. For the 24 students' fingerprint quality of slap left fingers, all r values for the force between 3.60N to 11.97N are greater than 0.889; and all r values for the force between 17.22N to 24.24N are less than -0.938. The mean μ and the standard deviation σ of r for the slap left fingers of 24 students are shown in Table 4. Table 3 and Table 4 indicate that there is a significant correlation between the fingerprint quality and force; fingerprint quality is strongly attributed to force, not

other factors. Therefore, too much force is the main reason for bad fingerprint quality because of the nonlinear elastic distortion that is resulted from the force.

Table 3. The correlation coefficient r of the fingerprint quality score and the force for the flat left thumb

| Force level (N) | From 0.98 to 9.39 | From 11.97 to 21.17 |
|-----------------|-------------------|---------------------|
| μ of r | 0.962 | -0.970 |
| σ of r | 0.0284 | 0.0318 |

Table 4. The correlation coefficient r of the fingerprint quality scores and the force for the slap left fingers

| Force level (N) | From 3.60 to 11.97 | From 17.22 to 24.24 |
|-----------------|--------------------|---------------------|
| μ of r | 0.966 | -0.972 |
| σ of r | 0.0290 | 0.0221 |

3.3. Non-parametric Analysis for Male Students and Female Students' Fingerprint Quality

14 male students and 10 female students participated in the fingerprint experiment. The author conducted a comparative study between the male and female students to compare the flat fingerprint quality of the left thumb at seven force levels and the slap fingerprint quality of left fingers at the next seven force levels, respectively. The author formulated the following null hypothesis:

There is no statistically significant difference in the fingerprint image quality between male and female students. The outcome is: the hypothesis is accepted or rejected at $\alpha = 0.05$. α is the level of significance.

The author used a non-parametric method to test the hypothesis. It is called the U test, the Wilcoxon test, or the Mann-Whitney test, named after the statisticians who contributed to its development. The major advantage of non-parametric methods is that no specific assumptions (such as normal distribution) about the population or the sample are required. Therefore, non-parametric methods can be used under more general conditions [15]. The U test is illustrated as follows:

Suppose that W_1 is the sum of the ranks of the values of the first sample (female students); W_2 is the sum of the ranks of the values of the second sample (male students) n_1 and n_2 are the first sample size and the second sample size, respectively. The statistic U is decided based on the following U_1 U_2 statistics:

$$U_1 = W_1 - \frac{n_1(n_1+1)}{2} \tag{5}$$

$$U_2 = W_2 - \frac{n_2(n_2+1)}{2} \tag{6}$$

Let U be the smaller of the values of U_1 and U_2 . The U test has the following criterion:

Reject the null hypothesis if $U \leq U'_\alpha$, where U'_α is given in Table VII [15]. $U'_\alpha = 36$ for $n_1 = 10$, $n_2 = 14$, and $\alpha = 0.05$. The U test results about the fingerprint quality of the flat left thumb and the fingerprint quality of slap left fingers are shown in Table 5 and Table 6, respectively. Table 5 indicates that there is no significant difference for flat fingerprint quality of the left thumb if the force is from 0.98N to 5.87N. There is significant difference if the force is from 9.39N to 21.17N. Table 6 indicates that there is significant difference for the fingerprint quality of slap left fingers at all seven force levels. The reason is that female students' fingers are softer. It is easier for female students' fingers (especially the little finger when the slap fingerprint is captured) to be affected by force and to produce greater non-linear elastic distortion.

Table 5. The U test for the fingerprint quality of the flat left thumb between male and female students at seven force levels ($U'_\alpha = 36$)

| Force level (N) | 0.98 | 3.47 | 5.87 | 9.39 | 11.97 | 17.22 | 21.17 |
|-------------------------|------|------|------|------|-------|-------|-------|
| U | 67.5 | 61 | 55 | 30 | 29 | 23 | 30 |
| Outcome: | | | | | | | |
| Significant difference? | No | No | No | Yes | Yes | Yes | Yes |

Table 6. The U test for the fingerprint quality of slap left fingers between male and female students at seven force levels ($U'_\alpha = 36$)

| Force level (N) | 3.60 | 6.18 | 9.39 | 11.97 | 17.22 | 21.17 | 24.24 |
|-------------------------|------|------|------|-------|-------|-------|-------|
| U | 34.5 | 23 | 28 | 23 | 15 | 13 | 16 |
| Outcome: | | | | | | | |
| Significant difference? | Yes | Yes | Yes | Yes | Yes | Yes | Yes |

4. CONCLUSION

Fingerprint images and quality scores captured through the ID 500 10-Print Live Scan System for both the flat left thumb and the slap left fingers indicate that too much or too little force leads to fingerprint quality problems. There are some breaks in the fingerprint image in the case of too little force; there are some dark areas in the fingerprint image and nonlinear elastic distortion in case of too much force.

Although dry finger skin, diseased fingers, sweaty fingers, or increased humidity, etc., can cause poor fingerprint images, the fingerprint quality of the 24 students in this study is strongly attributed to force (not other factors) according to the calculated correlation coefficient r and the correlation analysis. Too much force causes bad fingerprint quality because of large nonlinear elastic distortion that resulted from force.

The results obtained from the non-parametric method based on the U test indicate that there is a significant difference between male and female students in the fingerprint image quality of the flat left thumb at a greater force level and in the fingerprint image quality of the slap left fingers at all force levels when the level of significance α is 0.05. Female students' fingers are softer (especially the little finger for the slap fingerprint). It is easier for softer fingers to be affected by force and produce greater non-linear elastic distortion, which leads to the significant difference between male and female students.

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